Optimization of One-Dimensional Aluminum Foam Armor Model for Pressure Loading

Presenter: John C Goetz
Andrés Tovar
John Renaud
University of Notre Dame

SAE International™

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
12 APR 2011	**N/A**	**-**

4. TITLE AND SUBTITLE
Optimization of One-Dimensional Aluminum Foam Armor Model for Pressure Loading

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
John C Goetz; Andres Tovar; John Renaud

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Notre Dame

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA

10. SPONSOR/MONITOR'S ACRONYM(S)
TACOM/TARDEC/RDECOM

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
21757

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at SAE 2011 World Congress April 12-14, 2011 Detroit, Michigan, USA, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**16**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Break down

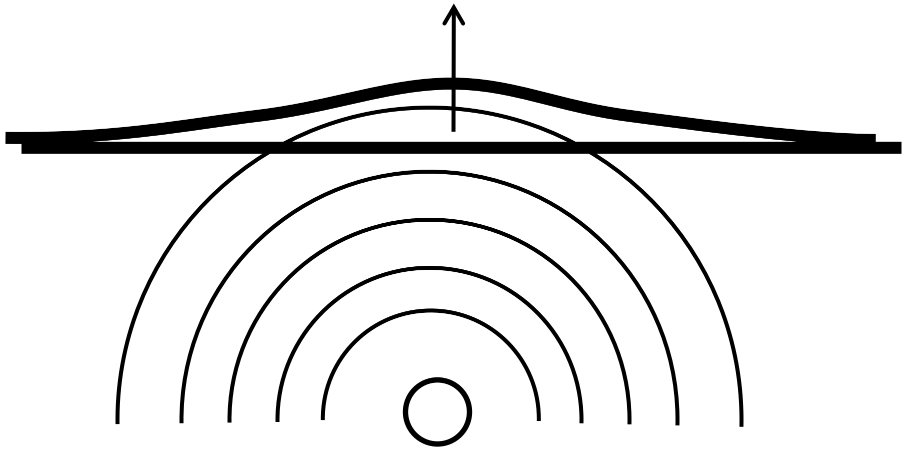
Optimization of One-Dimensional Aluminum Foam Armor Model for Pressure Loading

- Pressure loading
  - i.e. blast
- Aluminum Foam
  - i.e. cellular materials
- Optimization
  - Minimizing acceleration

The Blast Problem

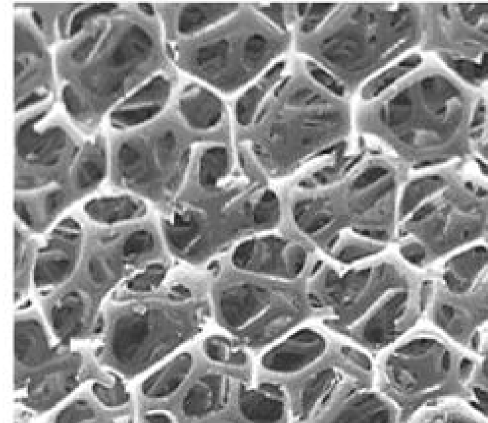
- Rapid expansion of a shockwave with high T and P emanating from a blast source
- Impact from a shock ***deforms*** and ***accelerates*** the receiving structure

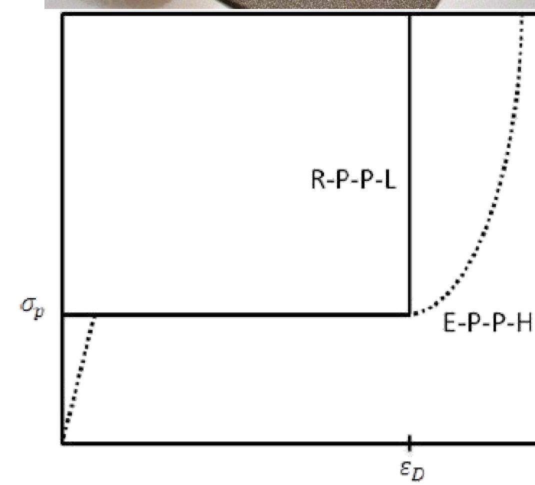
How to mitigate the effects of the blast?



Cellular materials

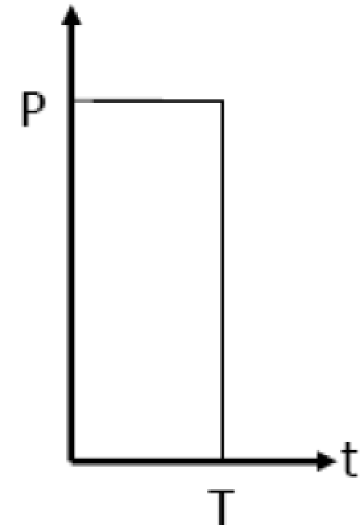
- Material that contains a repeated base cell structure
  - Foams
  - Honeycombs
- Characterized by
  - Low density
  - Cannot support tensile loadings
- Near ideal compressive deformation behavior:
  - Transmit minimal load
  - Absorb significant energy

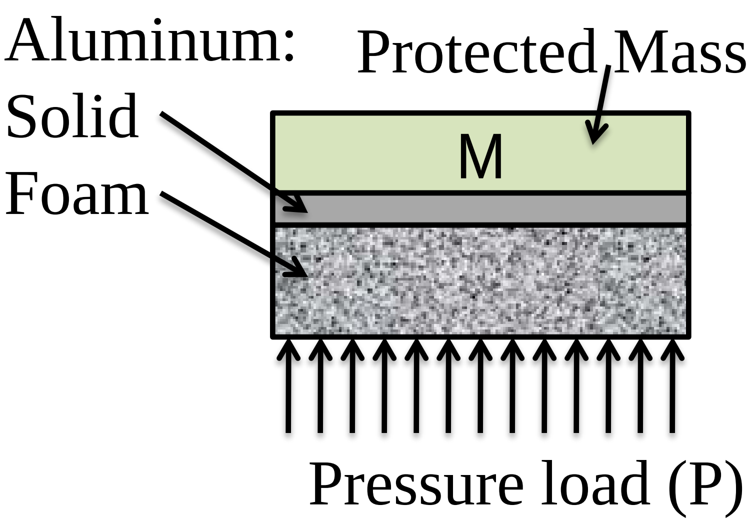




Problem Setup

- Objective:
  - To protect a mass from the <u>acceleration</u> effects of a pressure loading
- Modeling:
  - Pressure represented as a square pulse
  - Foam material properties are modeled as a function of relative density
  - System is modeled as series of springs and masses
  - System is unconstrained (inertial BCs)



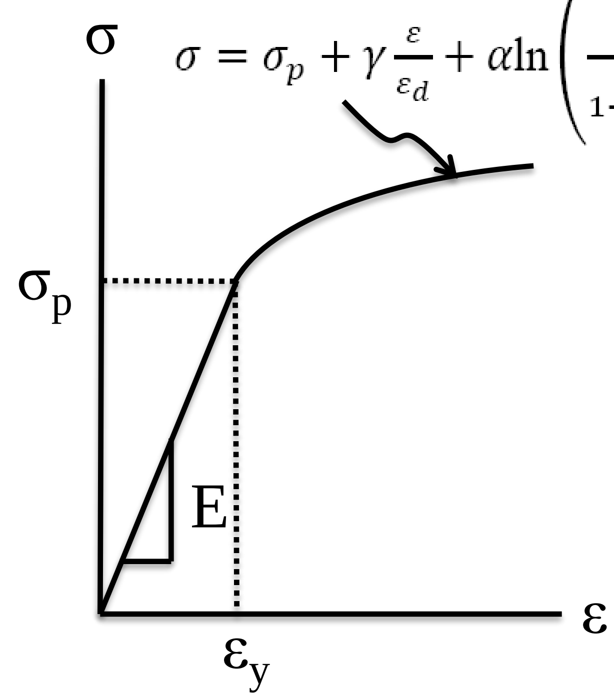


Material Properties

- According to Hanssen (2002), material parameters can be described with calibration functions
- Stress as a function of strain is then a function of the parameters

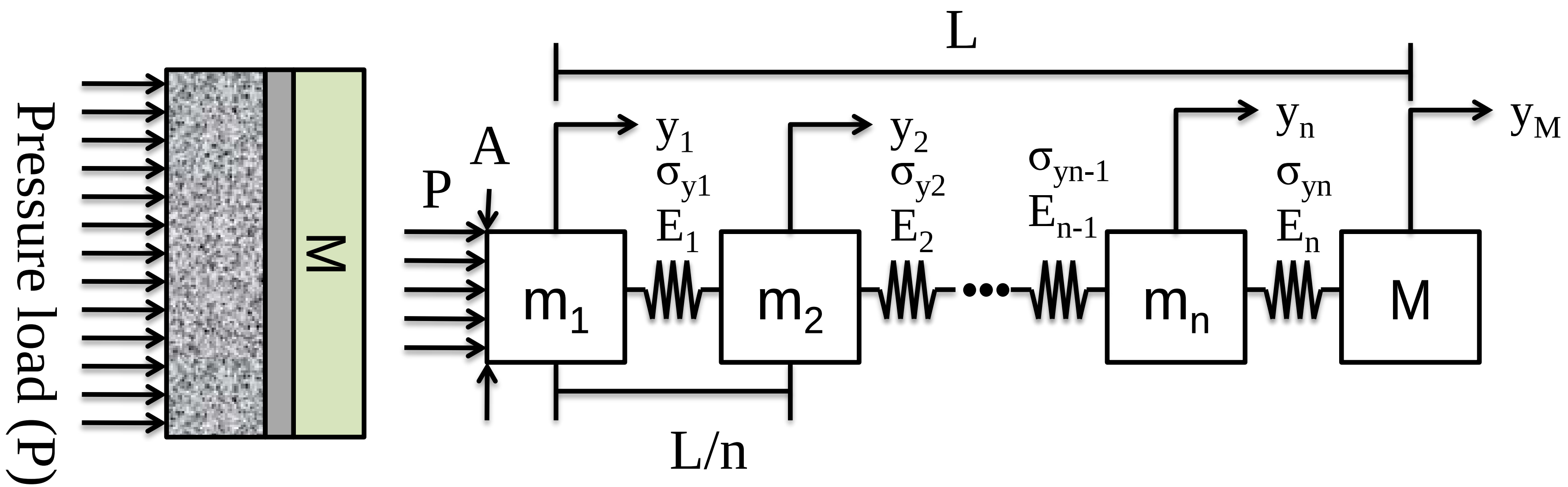
$$\left\{\sigma_p, \alpha, \frac{1}{\beta}, \gamma\right\} = C_0 + C_1 \left(\frac{\rho_f}{\rho_0}\right)^n$$

$$\sigma = \sigma_p + \gamma \frac{\varepsilon}{\varepsilon_d} + \alpha \ln\left(\frac{1}{1-\left(\frac{\varepsilon}{\varepsilon_d}\right)^{1/\beta}}\right)$$



System Model

- System model has an elastic-plastic spring based on the material properties of the given element joining each mass
- There are n+1 masses
  - n for the armor
  - 1 for the protected mass



Equations of Motion

$$m_i \ddot{y}_i = F_L - F_R = A(\sigma_L - \sigma_R)$$

$$m_i = \frac{\rho_i}{\rho_0}\frac{L}{n}A\rho_0 = x_i \frac{L}{n}A\rho_0 \qquad \omega^2 = \frac{T^2\sigma_{y0}}{\rho_0 L^2} \qquad \ddot{y}_i = \frac{\ddot{u}_i L}{T^2}$$

$$\boxed{\ddot{u}_i = \frac{AT^2\sigma_{y0}n}{x_i A\rho_0 L^2}\left(\frac{\sigma_{i-1}}{\sigma_{y0}} - \frac{\sigma_i}{\sigma_{y0}}\right) = \omega^2 \frac{n}{x_i}\left(\frac{\sigma_{i-1}}{\sigma_{y0}} - \frac{\sigma_i}{\sigma_{y0}}\right)}$$

$$\boxed{KE_{ND} = \frac{x_i}{2n\omega^2}\dot{u}^2 \qquad IE_{ND} = \frac{1}{n}\int_{\varepsilon_0}^{\varepsilon_f}\frac{\sigma_i}{\sigma_{y0}}d\varepsilon \qquad W_{ND}^{ext} = u_1\frac{P}{\sigma_{y0}}}$$

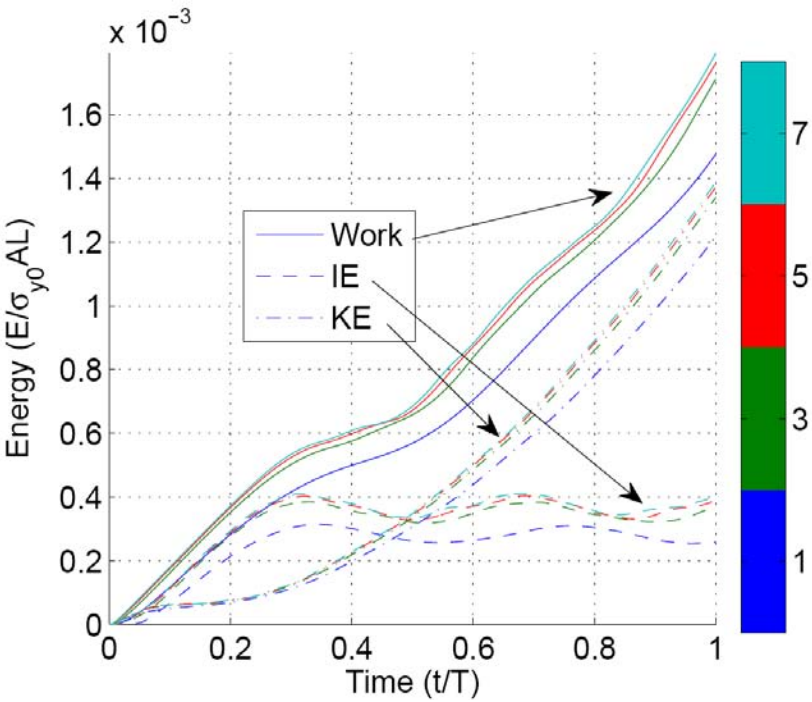
Model Parameters/Convergence

Total system length: L=.1m

Pressure Pulse duration: T=150μs

Protected Mass: M=100kg

Parameter	C_0	C_1	n
σ_p	0 (MPa)	720 (MPa)	2.33
γ	0 (MPa)	42 (MPa)	1.42
α	0 (MPa)	251 (MPa)	1
$1/\beta$	.1	15.7	3

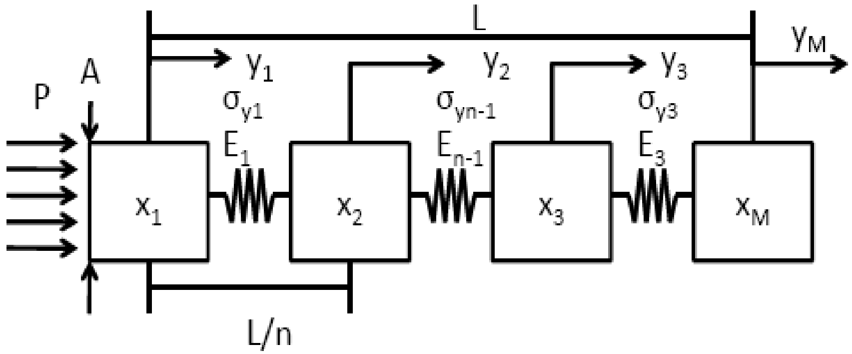


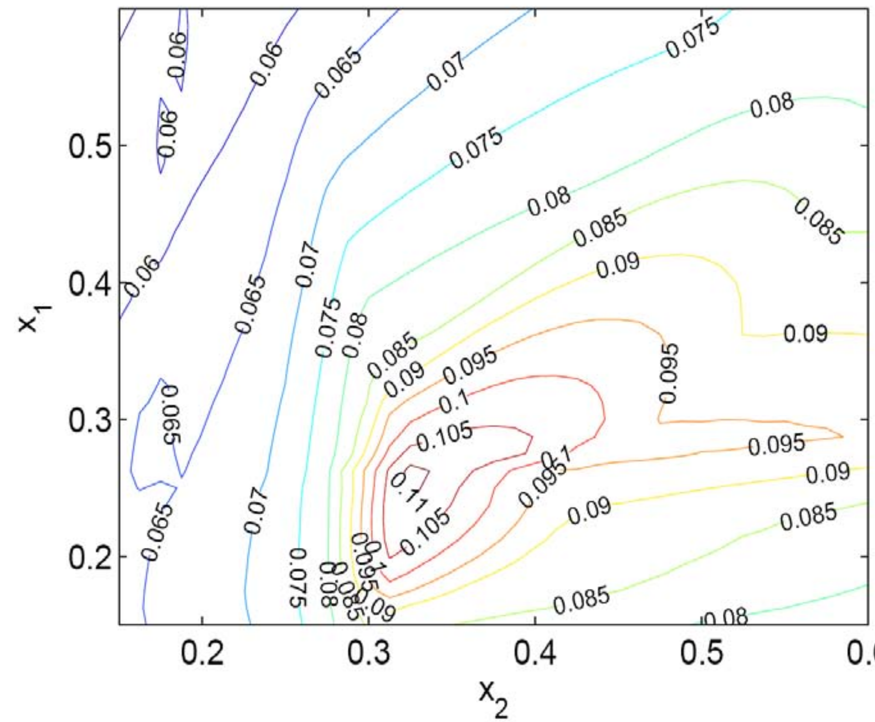
$$\sigma_{y0} = 276\ MPa$$
$$E_0 = 68.9\ GPa$$
$$\rho_0 = 2700\frac{kg}{m^3}$$

LOAD CASE 1: $\boldsymbol{P = 0.1\sigma_{y0}}$

$$\min_{x}\{\max \ddot{u}_M\}$$

$$s.t. \qquad x_L \le x_i \le x_U$$

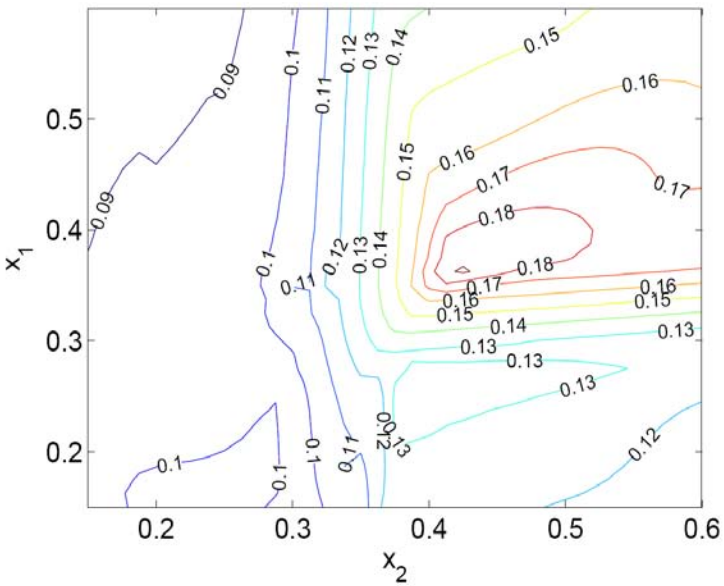




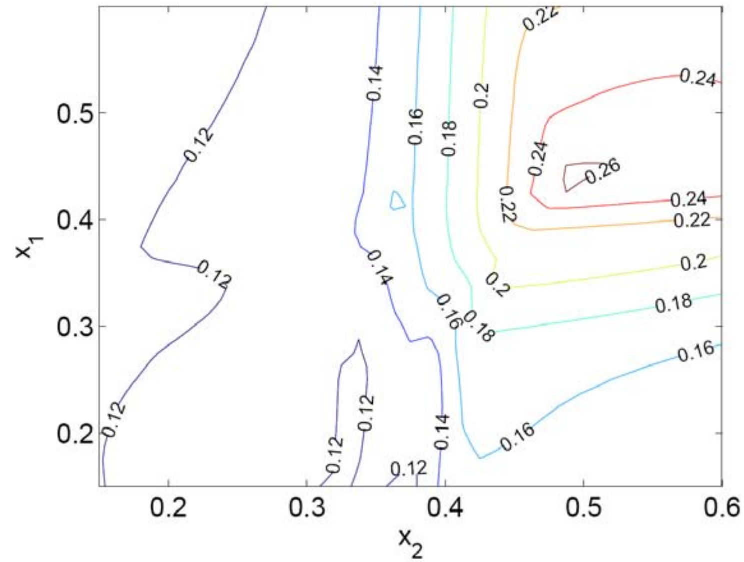
	x_1	x_2	
Graphical Solution:	**0.6**	**0.15**	**0.5423**

Higher Load Values

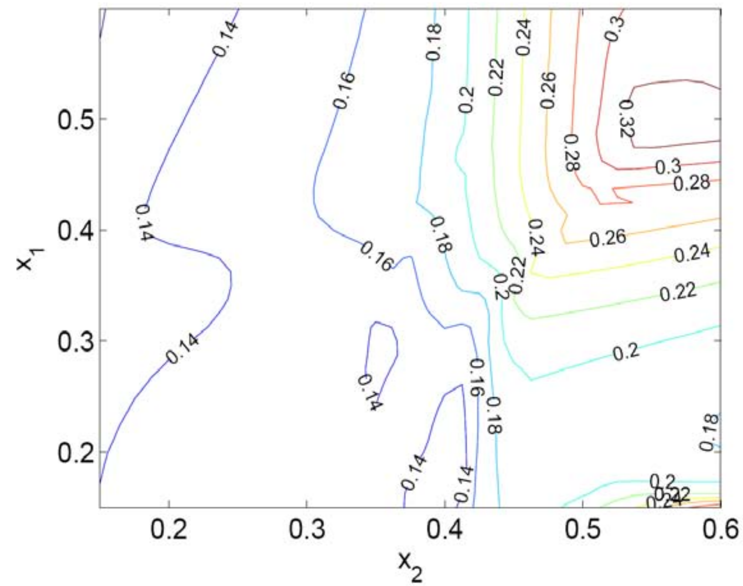
LOAD CASE 2: $P = 0.2\sigma_{y0}$



$$x_1 = 0.60 \text{ and } x_2 = 0.15$$

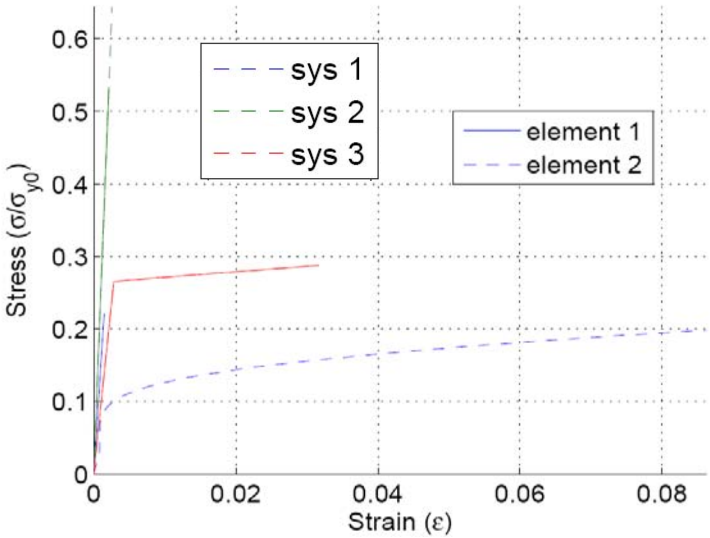


Solution space of 2DV acceleration minnimax problem with $P = 0.3\sigma_{y0}$



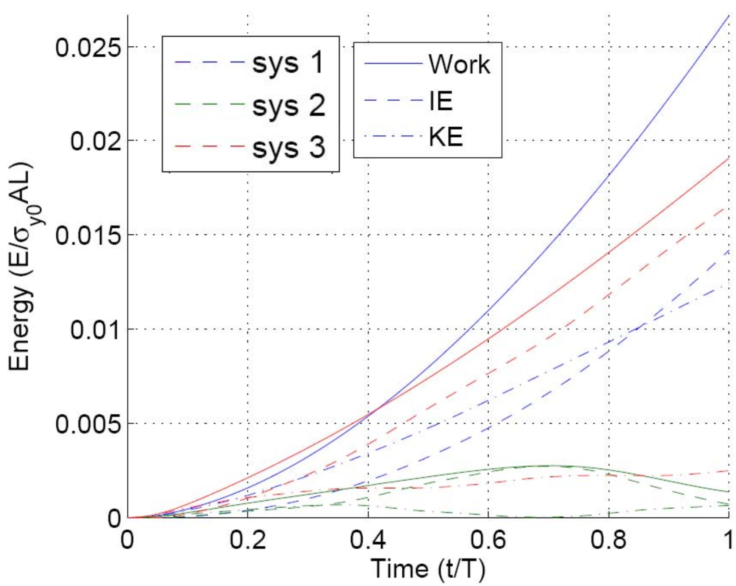
Solution space of 2DV acceleration minnimax problem with $P = 0.4\sigma_{y0}$

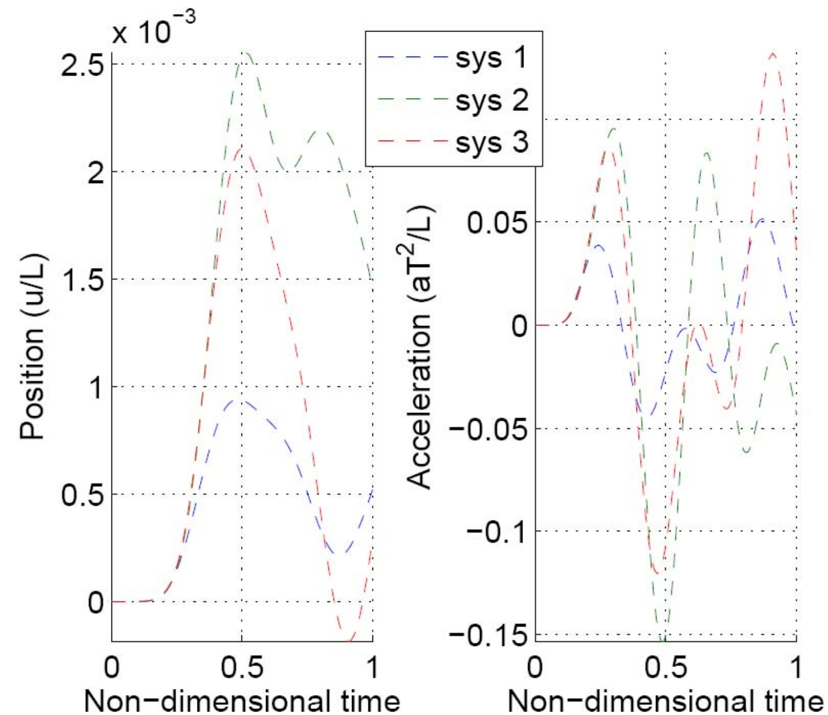
System Response Comparison



Relative densities of comparison systems

System->	1	2	3
x_1	0.6	1	0.375
x_2	0.15	1	0.375
x_3	1	1	1





Conclusions

- Found optimal design for 2 elements of foam
  - x_1 = .6 (highest density)
  - x_1 = .15 (lowest density)
- Observed that
  - More energy absorbed does not necessarily give the best result
  - Less work done by the blast can be worse than more work
  - Having more system kinetic energy

QUESTIONS?

This material is based upon work supported by the U.S. Army TACOM Life Cycle Command under Contract No. W56HZV-08-C-0236, through a subcontract with Mississippi State University, and was performed for the Simulation Based Reliability and Safety (SimBRS) research program.

Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Army TACOM Life Cycle Command.

BACKUP

Material properties

- Yield stress and elastic modulus depend on
  - Relative density (density of foam/density of solid
  - Distribution constant (open cell vs closed cell)
- Compaction strain is only a function relative density

Relative density

$$\frac{\sigma_p}{\sigma_{y0}} = 0.3\phi^{3/2}\left(\frac{\rho_f}{\rho_0}\right)^{3/2} + (1-\phi)\left(\frac{\rho_f}{\rho_0}\right)$$

$$\frac{E_f}{E_0} = 0.3\phi^2\left(\frac{\rho_f}{\rho_0}\right)^2 + (1-\phi)\left(\frac{\rho_f}{\rho_0}\right)$$

$$\varepsilon_d = 1 - 1.4\left(\frac{\rho_f}{\rho_0}\right)$$